Estimating the Celestial Reference Frame via Intra-Technique Combination

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Abstract One of the primary goals of Very Long Baseline Interferometry (VLBI) is the determination of the International Celestial Reference Frame (ICRF). Currently the third realization of the internationally adopted CRF, the ICRF3, is under preparation. In this process, various optimizations are planned to realize a CRF that does not benefit only from the increased number of observations since the ICRF2 was published. The new ICRF can also benefit from an intra-technique combination as is done for the Terrestrial Reference Frame (TRF).

Here, we aim at estimating an optimized CRF by means of an intra-technique combination. The solutions are based on the input to the official combined product of the International VLBI Service for Geodesy and Astrometry (IVS), also providing the radio source parameters. We discuss the differences in the setup using a different number of contributions and investigate the impact on TRF and CRF as well as on the Earth Orientation Parameters (EOPs). Here, we investigate the differences between the combined CRF and the individual CRFs from the different analysis centers.

Keywords VLBI, ICRF, intra-technique combination, datum-free normal equations, full variance-covariance information

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1 Introduction

Very Long Baseline Interferometry (VLBI) is the unique space-geodetic technique for the generation of the International Celestial Reference Frame (ICRF), one of the fundamental products of the International VLBI Service for Geodesy and Astrometry [8]. To date, two realizations of the International Celestial Reference System (ICRS) have been computed, and the third one [7] is under construction. The latest realization, the ICRF2 [4], consists of precise positions of 3,414 sources, including 295 defining sources. Furthermore, 2,197 out of the 3,414 sources were observed only in VLBA Calibrator Survey (VCS, e.g., [2]) sessions, which are special astrometric survey sessions, optimized to observe a huge number of new radio sources. Both previous realizations were computed by a single analysis center, the VLBI group at the NASA Goddard Space Flight Center (GSFC), using a single software package, Calc/Solve.

While the benefit of the intra-technique combination of various analysis centers for the Terrestrial Reference Frame (TRF) and Earth Orientation Parameters (EOPs) is well known [3] and has been utilized for the official IVS products for many years, only comparisons between source catalogs of different analysis centers were made for the computation of the ICRF2. Due to the fact that today most of the IVS analysis centers routinely produce contributions containing radio source positions, an intra-technique combination is equally feasible for the generation of a CRF. For this reason, a rigorous combination procedure for CRF determinations has been proposed in Iddink et al. [5, 6].

The developed approach is based on the combination at the level of datum-free normal equation systems (NEQs), which enables the rigorous transfer of the full variance-covariance information of all individual input contributions and all related parameters. Furthermore, it is guaranteed that the contributions are not distorted by any constraints before combining them. Thus, the same a priori frames and an identical datum can be applied to all contributions within the combination process. Since high precision geodetic VLBI started operating in 1979, over 5,500 sessions have been observed and analyzed by several analysis centers. These sessions are freely available on the server of the IVS and can be used for the combination on a session-by-session level.

Additionally, various campaigns have been performed to sample the southern hemisphere with a better density, and the VCS has been redone. Further optimizations of the ICRF3 [7] with respect to the previous versions will be obtained on the analysis side. Following IUGG Resolution No. 3 (2011) this approach can then easily be extended to a consistent estimation of CRF, TRF, and the EOPs, based on the observations of different space-geodetic techniques. Based on all these NEQs generated by different analysis centers, individual CRFs can be computed and assessed.

In this paper we focus on the usability of the different contributions in terms of generating a reliable combined CRF. This includes the investigation of the differences between the combined CRF and the individual CRFs from the different analysis centers. The whole combination process as well as the illustration and assessment is done with our new VLBI software package ivg::ASCOT [1]. Here we also give an insight into the main capabilities of our SINEX analyzer toolbox.

2 Combination Setup

At the beginning it is sensible to use a set of sessions that is small and only comes from a few different analysis centers. This gives us the opportunity to detect blunders within the combination process and the individual contributions.

The rough combination procedure can be summarized as follows:

- selection of sessions,
- selection of analysis centers,
- stacking of related NEQs,
- defining the datum and solving the system,
- illustration and intepretation of the results.

In order to assess the general functionality of the combination procedure implemented in ivg::ASCOT, we started using the contributions of two well-known and established analysis centers: the United States Naval Observatory (USNO) and the Goddard Space Flight Center (GSFC). Both analysis centers are using the software package Calc/Solve. For further simplification only 15 sessions from CONT14 were used to generate a short-term CRF, TRF, and corresponding EOPs. Hence, in our initial combination only 30 NEQs were stacked using the freely available SINEX files containing the pre-reduced datum-free NEQs. The station coordinates were set up as global parameters in order to obtain a single station position over the whole period of CONT14. All EOPs as well as all special handling sources were set up on a daily basis. The remaining sources were stacked and set up as global parameters. In order to be able to solve the stacked monolithic system, an NNR/NNT datum was applied to the stations and an NNR datum to the sources.

Finally, we obtained a combined CRF, TRF, and corresponding EOPs. Additionally, we performed the same procedure twice only using the sessions of each Analysis Center individually. Thus, we were able to compare the individual CRFs and TRFs to the combined one by means of a Helmert transformation. With respect to the CRF, the transformation was based on the ICRF2 defining sources and w.r.t. the TRF on a set of well-established stations. After transforming the catalogs onto each other, the residuals between corresponding sources/stations can be computed and illustrated. In the following we focus on the CRF.

3 Initial Results

The solution residuals of GSFC are illustrated in blue (dark), and the residuals of USNO are shown in green (light) (see Figure 1). As one would expect, the residuals are perfectly symmetrical and always point into the opposite direction. This is because only two contributions were used, and both contributions were weighted equally. Furthermore, due to the fact that both analysis centers used the same software package and only a short time period was selected, it is reasonable that

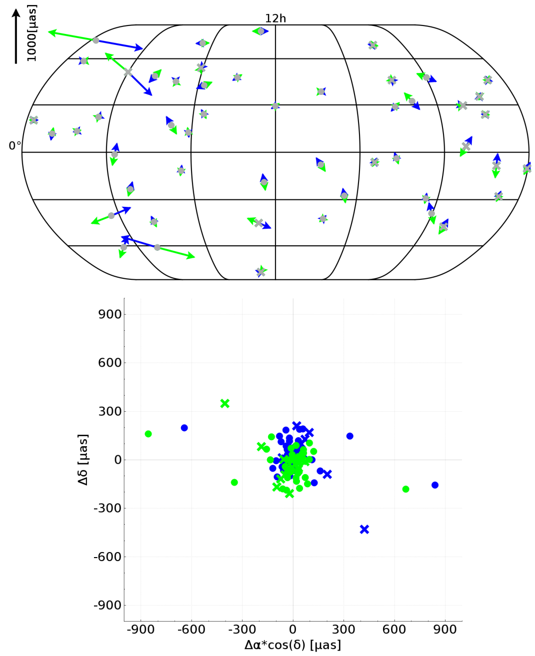

Fig. 1 Residuals between the combined and individual solutions using CONT14: GSFC (blue/dark), USNO (green/light).

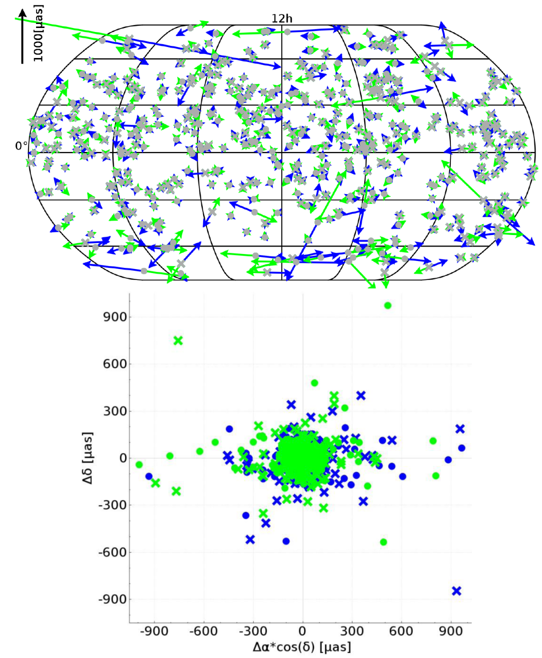

Fig. 2 Residuals between the combined and individual solutions using R1/R4 between 2010 and 2014: GSFC (blue/dark), USNO (green/light).

all residuals are quite small and even not visible at this scale.

In the next step the whole solution setup was retained, but the time period was expanded. In the next solution setup (see Figure 2), we used all official R1 and R4 sessions between 2010 and 2014 analyzed at GSFC and USNO, and we performed the same combination procedure as already explained. Additionally to the CRF plot using arrows for illustrating the differences, the lower plots in Figure 1 and Figure 2 show the same residuals in a more vivid way. Here we also see the same expectable symmetric behavior of the differences between the individual solutions and the combined one after the transformation onto each other. The defining sources are represented by a disc while all other types of sources are illustrated by a cross.

Table 1 Rotation angles and their standard deviations between combined catalog and individual catalogs related to Figure 2 and Figure 4.

Anal. Center	x [mas]	y [mas]	z [mas]
GSFC	-0.002 ± 0.003	0.001 ± 0.003	-0.002 ± 0.003
USNO	0.001 ± 0.003	0.000 ± 0.003	0.002 ± 0.003

In general, the estimated rotation angles (see Table 1) and their standard deviations as well as the big residuals of some weak sources in the far southern and northern hemispheres match the expectations. In summary, the results in Figure 1 and Figure 2 should demonstrate the successful performance of the general combination procedure and the subsequent analysis and plotting toolbox of ivg::ASCOT.

After the step of expanding the time period for two analysis centers, more analysis centers needed to

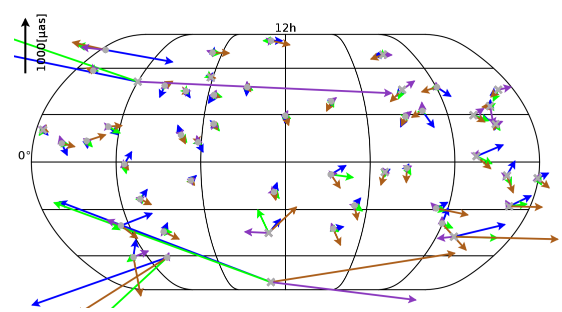

Fig. 3 Residuals between the combined and individual solutions using CONT14: GSFC (blue), USNO (green), DGFI (brown), CGS (purple).

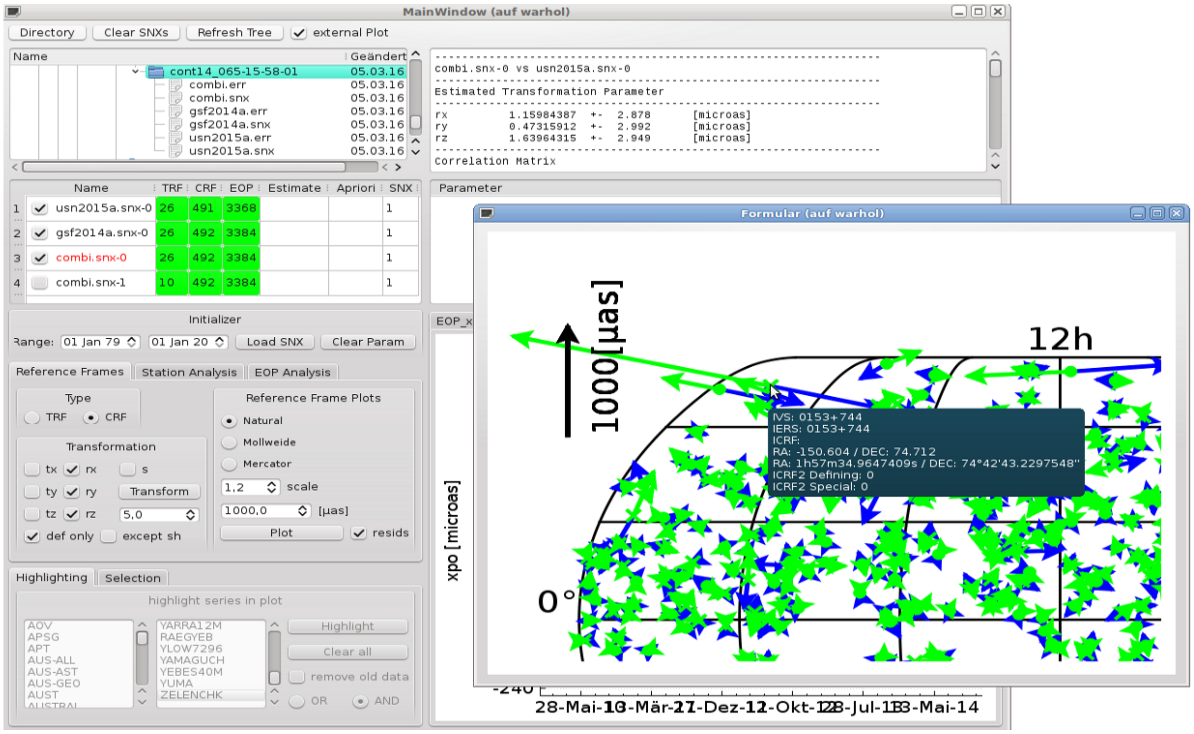

Fig. 4 Example of using the ivg::ASCOT SINEX analyzer. Individual (USNO, GSFC) and combined results are loaded and transformed on each other by means of a Helmert transformation. The residuals are illustrated in an external plot. The zoom functionality and the tooltips enable the analysis of source specific information (e.g., position, different names, defining or special handling).

be included in the combination. For this purpose the time range was again limited to only 15 sessions of CONT14, but now two additional analysis centers were used: the German Geodetic Research Institute (DGFI) and the Centro di Geodesia Spaziale (CGS). Hence, four analysis centers contributed to the combined CRF solution illustrated in Figure 3, using the same combination setup as in the previous cases.

When comparing the residuals of Figure 1 and Figure 3, it becomes obvious that most of the residuals are comparable in terms of their magnitude. Nevertheless there are about five sources with big striking residuals pointing in different directions. After some deeper investigations into this issue using the ivg::ASCOT SINEX analyzer toolbox (see Figure 4) it has become clear that all of these sources have only a few observations within CONT14.

The resulting problem is that the use of Calc/Solve combined with an unsuitable configuration setup leads to the issue that these specific sources are not stored in the NEQs and therefore not saved in the SINEX files. Because of this, these weak sources with only a few observations lead to hidden constraints within the affected NEQs. Hence, the in-the-proper-sense datum-free NEQs are not datum-free anymore and cannot be rigorously combined with other contributions.

In the case of the combined results illustrated in Figure 3, the exclusion of the CGS contribution from the combination prevents the occurrence of the huge residuals because of this issue.

4 Conclusion and Future Work

We have shown that we are able to generate a combined CRF based on different contributions using our newly developed VLBI software package ivg::ASCOT. Between two and four analysis centers were used, and between 15 and 400 sessions were stacked. In order to generate a reliable combined CRF, investigations concerning the features and properties of a combined CRF based on more sessions and more analysis centers have to be made. Furthermore we found out that it is absolutely mandatory to store all observed sources within the NEQs and the SINEX files, independent of the number of observations.

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